and resolution of marine biological work in Antarctica. In the last decade there has been a significant shift in approach, with sampling increasingly targeted at answering specific questions, improved synergy with other disciplines, and a widespread application of molecular technology. This has been driven by the recognition that rapid regional warming was inducing striking changes in the environment, and the awareness that change in Antarctica had a truly global impact. Marine biology has recently become a key tool in understanding change in carbon cycling, the reconstruction of Antarctica's glacial history and thereby in predicting potential ice sheet behaviour and consequent sea level rise. Marine biological work in Antarctica has much to do, and remains an important aspect of trying to understand the world we live in and how it will change in the future.

Further reading

Atkinson, A., Siegel, V., Pakhomov, E., and Rothery, P. (2004). Long-term decline in krill stock and increase in salps within the Southern Ocean. Nature *432*, 100–103.
Aronson, R.B., Moody, R.M., Ivany, L.C., Blake, D.B., Werner, J.E. and Glass, A. (2009). Climate Change and Trophic Response of the Antarctic Bottom Fauna. PLoS ONE 4, e4385. doi:10.1371/journal.pone.0004385.
Barnes, D.K.A., and Hillenbrand, C.-D. (2010). Faunal evidence for a late quaternary trans-Antarctic seaway. Glob. Change Biol. *16,* 3297–3303.
Brandt, A., Gooday, A.J., Brandão, S.N., Brix, S., Brökeland, W., Cedhagen, T., Choudhury, M., Cornelius, N., Danis, B., De Mesel, I., *et al.* (2007). First insights into the biodiversity and biogeography of the Southern Ocean deep sea. Nature *447*, 307–311.
Griffths, H.J. (2010). Antarctic marine biodiversity – What do we know about the distribution of life in the southern ocean? PLoS ONE *5(8)*, e11683.
Gutt, J., and Piepenburg, D. (2003). Scale-dependent impact on diversity of Antarctic benthos caused by grounding of icebergs. Mar. Ecol. Prog. Ser. *253*, 77–83.
Janosik, A.M., and Halanych, K.M. (2010). Unrecognized Antarctic biodiversity: a case study with *Odontaster* (Odontasteridae; Asteroidea). Integr. Comp. Biol. *50*, 981–992.
Rogers, A.D., Murphy, E., Clarke, A., and Johnston, N. (2007). Antarctic ecology: from genes to ecosystems. Phil. Trans. Roy. Soc. *362,* parts 1 and 2.
Schiaparelli, S., and Hopcroft, R.R. (2011). Census of antarctic marine life: Diversity and change in the southern ocean ecosystems. Deep Sea Res. II *58*, 1–276.
Thomas, D.N. (2004). Frozen Oceans. (London: Natural History Museum).
Trivelpiece, W.Z., Hinke, J.T., Miller, A.K., Reiss, C.S., Trivelpiece, S.G., and Watters, G.M. (2011). Variability in krill biomass links harvesting and climate warming to penguin population changes in Antarctica. Proc. Natl. Acad. Sci. USA *108*, 7625–7628.

British Antarctic Survey, NERC, Madingley Road, Cambridge, CB3 0ET, UK.
E-mail: dkab@bas.ac.uk

Essay

Could Scott have survived with today's physiological knowledge?

In 1911, members of a British expedition walked across the Antarctic to the South Pole, but in the punishingly hostile environment, retracing their steps back to the edge of the continent proved fatal. Over the last 100 years, knowledge about human physiology has greatly increased and, on the centenary of this most extreme of all journeys, this essay explores the true extent of the physiological stress experienced by the men involved and whether their fate was inevitable.

Lewis George Halsey[1]* and Mike Adrian Stroud[2]

One hundred years ago, Captain Robert Falcon Scott set out across the Ross ice shelf in the Antarctic hoping to be the first person in history to reach the South Pole. He was travelling on foot. Although his team of five men succeeded in crossing the 900 miles from the edge of the continent to 90° latitude, man-hauling their sledges carrying food and equipment for most of the trip and conducting valuable science en route, they died on the return journey. A century on, there is still controversy about how much Scott (Figure 1) was at fault, although in 1910 there was considerable ignorance about the physiological stresses caused by Antarctic extremes. Accepting the limitations of the technologies he took on the expedition, today we can use our greatly advanced understanding of the human condition to assess the major physiological stressors that Scott endured and the tricks he missed to limit them. In celebrating this centenary and the vast development in physiological knowledge accrued since the 'Heroic Age' of Antarctic exploration, we ask whether, with this modern insight, Scott's team could have survived their epic journey.

Antarctica is a desolate landscape. Temperatures there are usually below 0°C and regularly as low as –70°C, exacerbated by very strong katabatic (downslope) winds, and there is little vegetation or animal matter for food. This explains why Antarctica is the sole continent not permanently inhabited by people, and terrestrial travel there is incredibly demanding.

Early Antarctic explorers hoped that exposure to a cold environment over months would trigger noteworthy physiological adaptations to help them cope, but it is now recognised that this does not happen. As a consequence of our African ancestry, mankind is primarily adapted to heat exposure, and responses to the cold are not only relatively ineffective [1] but can be counterproductive for man-hauling expeditions. For example, alongside shivering to generate more heat, the body increases insulation by vasoconstriction of blood vessels primarily in the skin, such that less heat is transported by the blood to body extremities and lost. However, the increase in insulation from this response is less than that provided by wearing a typical business suit, and the marked reductions in blood flow to the extremities considerably increase

Figure 1. Captain Scott, 1911.
Photograph by Herbert Ponting. Reproduced with permission of the Scott Polar Research Institute, University of Cambridge.

Figure 2. Scott's polar party near the South Pole, 1912.
Photograph by Henry Bowers. Reproduced with permission of the Scott Polar Research Institute, University of Cambridge.

the risks of frostbite (the growth of ice crystals in and around cells). Scott and his men smoked and while this was unlikely to affect their ability to pull their sledges, as the pace of doing so is slow, we now know that smoking promotes further peripheral vasoconstriction.

From the earliest land explorations of the Antarctic it has been clear that, during man-hauling journeys, by far the most effective way of staving off the cold is through the work of pulling the sledges. This produces considerable heat as a valuable by-product of muscle inefficiency. Today we can quantify this; for example, multiple layers of clothing are necessary to alleviate shivering in a stationary person at 5°C, while trousers and a jacket are sufficient at –18°C if activity levels are high. For these reasons, Scott's layers of predominantly cotton and wool clothing would have initially served him well, being somewhat windproof and providing often more than sufficient insulation while on the move, though these qualities would have deteriorated when perspiration froze within the layers. Greater insulation — for example, provided by furs — would have created much more perspiration resulting in body fluid loss and reduced material integrity. It is during times of lower work levels that the body is at most risk from the cold, with periods erecting a tent in Antarctica being particularly dangerous.

Furthermore, the effects of cold are exacerbated in individuals with lower fat and muscle levels, as the amount of energy lost to shivering increases while the effectiveness of exercise and shivering at heating up the body core becomes progressively less. This is of key importance to the Antarctic man-hauler, whose biggest threat is massive weight loss as the energy expended keeping warm in cold conditions and pulling a heavy sledge on an icy terrain that is often soft or sticky is so high that it is not met by the available food rations. To account for the resultant calorie debt, the body has to utilise its own tissues as sources of energy. Additionally, if weight loss is so extensive that fat and protein reserves are nearly exhausted, the body is forced to consume tissues vital for existence, such as body organs, and so physiological functions start to deteriorate, including a marked reduction in cardiovascular capacity. With a weakened physiological integrity, other factors such as dehydration and sleep deprivation may become more prominent and have additional damaging effects. Ultimately, metabolic rate decreases to a point where insufficient heat is produced and too much is lost to prevent deep hypothermia and death. This spiralling deterioration undoubtedly played a large part in the demise of Scott and his men.

Unfortunately, Scott was not aware of how much weight his team would lose during their journey. In 1910, despite early pioneering work on metabolic rate by researchers such as Zuntz [2], who was ahead of his time in measuring the oxygen consumption of people climbing in the Alps using a portable gas analyser, there was little understanding of the power output needed to tow a sledge, Scott's sledges weighing over 100 kg fully laden (Figure 2). In fact, it was not until one of us (Mike Stroud) measured energy expended by men during polar expeditions during the 1980s and 90s that the extreme energy cost of pedestrian polar travel was appreciated. For example, while Stroud and Sir Ranulph Fiennes were crossing Antarctica on foot in 1992/93, each of them expended on average nearly 7,000 kcal per day, and during a 10 day period ascending over 2,000 m up a glacier to the polar plateau, this increased to nearly 11,000 kcal [3]. Indeed, sledge-pulling up to the polar plateau expends energy at a much higher daily rate than even that of Tour de France competitors [4]. From such modern expeditions we can reasonably estimate that Scott's 140 day, 1,600 mile journey to the South Pole (Figure 3) and return part way, which included small deviations to geologise, resulted in each man expending up to 1,000,000 kcal.

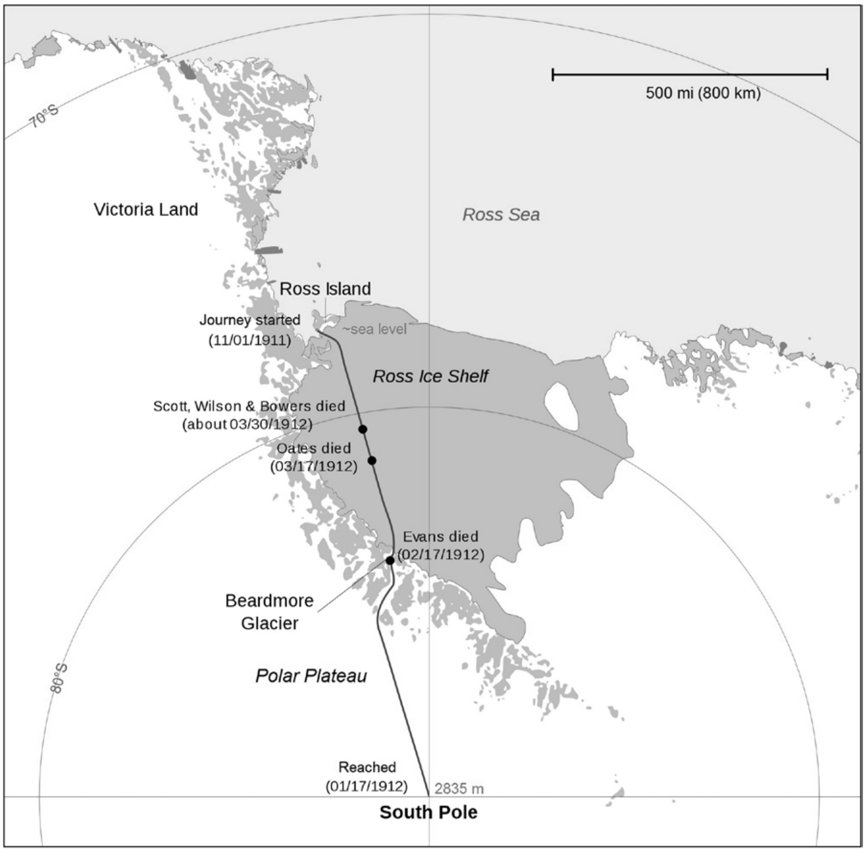
In contrast, Scott's understanding of the provisions necessary to sustain man-hauling came from a previous expedition in 1908 to the Antarctic by Ernest Shackleton, the first to reach the polar plateau. His team returned to their base close to death having taken cocaine to extend marching times on the return journey in a desperate bid to make it home. Shackleton's expedition concluded (incorrectly) that the daily rations required to reach the pole amounted to 34 ounces (964 g) [5], close to the average weight of rations that Scott chose to use, which provided an average of 4,400 kcal per day [6]. Scott's team are therefore likely to have experienced a daily calorie deficit of at least 2,000 kcal each and lost around 1.5 kg of body mass per week. As a result, Scott had lost about 40% body weight by the time of his death. Because Scott did not anticipate the scale of his daily calorie deficit, unlike modern man-haulers he made no real efforts to gain weight prior to his journey.

Because the energy content of macronutrients had been measured around the turn of the century, Scott knew that the energy density of fat is particularly high and hence his rations had a high fat content, even though this made them close to unpalatable for his team at the start of their journey. The version for the polar plateau consisted of biscuit, pemmican, butter, sugar, cocoa and tea, which provided per day up to 210 g of fat (24% of the ration), 257 g of protein (29%) and 417 g of carbohydrate (47%) [6]. However, his rations still contained less fat, and considerably more protein, than now thought optimal. More recent man-hauling expeditions in the Antarctic have used rations that contain around 5,000 kcal [3] of energy yet are of similar weight to those used by Scott, because modern rations consist of 57% fat and only 8% protein.

Although a diet containing around 70% energy as carbohydrate has become the conventional intake for enhanced endurance in marathon runners [7], the slow, plodding work of man-hauling is less affected by oxygen limitations and so better suited to fat utilization. Furthermore, high levels of fat ingestion are likely to increase the time that intense man-hauling can be sustained, because the body's glucose stores will be depleted within the first two to three hours of working (such depletion in marathon runners results in them hitting the infamous 'wall') and the inevitable fatigue beyond this is lessened by optimal fat oxidation, which is triggered by consistently consuming a high fat diet [3]. Early studies of protein needs postulated that muscles were partially broken down during contractions to supply energy, which encouraged Scott to believe that the high levels of muscular exercise during man-hauling demanded very high levels of protein ingestion and explains why he included huge amounts of protein in his rations. Today, however, it is recognised that a better strategy to limit muscle loss is to minimise the overall energy deficit whilst providing sufficient carbohydrate to protect protein stores from being converted to glucose as an energy source [8].

Figure 3. Scott's polar party at the South Pole, 1912.
Photograph by Henry Bowers. Reproduced with permission of the Scott Polar Research Institute, University of Cambridge.

Just over a month into the journey, Scott and his men had crossed the Ross ice shelf and reached the base of the Beardmore Glacier. They commenced a near two-week ascent from sea level to an altitude of around 2,500 m; the edge of the polar plateau (Figure 4). The specific challenge of the plateau is hypoxia, as the partial pressure of inspired oxygen averages around 510 mmHg, 30% less than at sea level. Most of our present understanding of human physiology at altitude has only been obtained in the last 50 years, catalysed by the 'Silver Hut' expedition on Mount Everest in 1960. Consequently, we now know that, in contrast to the cold, human physiology responds considerably to altitude. Acclimatization to low oxygen levels, via hypoxia-sensitive gene and protein expression, enhances the efficiency of cellular respiration and over several weeks, haemoglobin concentration increases due to the increased production of red blood cells and a decrease in blood volume due to excess urination. Because man-hauling to the plateau is a gradual process, upon reaching it an explorer already enjoys valuable physiological acclimatization. Furthermore, as altitude increases up to 3,500 m, the oxygen content of blood falls quite slowly as a result of the continued strong acceptance of oxygen molecules by haemoglobin in the blood. Nevertheless, due to the great exertion of man-hauling, all effects of altitude are intensified, including fatigue, poorer sleep, possibly faster weight loss and, perhaps particularly debilitating, dehydration. There is clear evidence of altitude sickness from the diaries of Scott's party, who spent over 50 days on the plateau, but it is now known that time at altitude also results in subtler problems which are nonetheless crucial to the polar man-hauler, including reduced physical performance [9] and impaired concentration and judgement [10]. Antarctic explorers today are generally aware of the psychological disruptions caused by altitude and also ensure that they drink copiously in such environments.



Current Biology

Figure 4. The route to the South Pole.
The route taken by Scott and his men during their journey to the South Pole from Ross Island, which ended in their deaths during the return leg as they retraced their steps. Due to the persistent presence of the Ross ice shelf it is possible to walk from Ross Island to the Antarctic land mass.

While Scott had taken considerable interest in the proportions of macronutrients in his rations, he understandably gave little thought to micronutrients, because vitamins were not recognised until after his time. Around the start of the 20th century there was a range of theories proposed by the scientific community [11] on the causes of scurvy, the most prolific and pernicious of diseases experienced by expedition parties, which has debilitating symptoms such as suppurating wounds. These theories were in the main misinforming and resulted in a distinct lack of clarity for Scott about the best foods to prevent scurvy in his men during their journey to the Pole.

Today it is known that ascorbate is an ion of vitamin C required for essential metabolic reactions which notably include the synthesis of collagen. Thus, vitamin C is necessary for the growth and repair of body tissues, including generating skin, scar tissue and tendons. With just a few exceptions, such as bats and guinea pigs, most mammals including humans must obtain vitamin C via ingestion. Unbeknown to Scott, it was probably only the pony meat he ate semi-raw, once these transport animals had been slaughtered on the outward journey to the pole, which provided a small supply of this crucial micronutrient.

After around 11 weeks of travelling, Scott had reached the Pole. But although the longest the body can store ascorbic acid is about 12 weeks, which is the time taken for scurvy to become manifest on a diet completely free of vitamin C, it is unclear whether Scott or any of his four men actually suffered from the disease during their return journey. Edward Wilson, the group’s physician, made no mention of relevant symptoms in his diaries despite well-observed and detailed notes, yet Edgar Evans’ body showed signs of poor wound repair such as a rotting nose and suppurating hand laceration. Modern Antarctic adventurers never have scurvy, eating fortified freeze-dried vegetables and meat in their rations along with consuming high-dose multivitamin tablets.

So what conclusions can we draw about Scott’s chances of returning to the continent’s edge had he been armed with modern physiological understanding? The hardship of man-hauling in Scott’s time was without doubt exacerbated by the less advanced technologies available, most notably in terms of clothing, sledges and fuel storage. However, modern-day, unsupported explorers still experience the same gamut of physiological stresses, particularly because, although their equipment is superior, that superiority enables them to pull larger loads for longer. In fact, technology aside, there is perhaps a surprisingly limited amount that can be done differently today in light of modern knowledge. The single major difference in the physiological management of the modern Antarctic man-hauler revolves around the diet consumed, with significantly higher calorie intakes each day and the proportions of macronutrients now favouring fat and carbohydrate over protein. Modern rations also include micronutrients in abundance.

Given that Scott and his last two companions faltered on their return journey just 11 miles from the next food depot, an enhanced diet based on today’s physiological wisdom probably would have ensured their survival. Most importantly, they would have had more strength, more fat insulation and a greater ability to recover and heal after each period of man-hauling. Whether this would have been sufficient to make the difference for Evans and Lawrence Oates, who both died earlier, is less clear, particularly as Evans fell around 250 miles before Scott did. Thus, it is likely that, without rations very much higher both in calories and vitamin C, neither being an option for Scott and only the latter possible today, Evans was never going to make it home. Modern physiological understanding may not therefore suffice to protect everyone on Antarctic man-hauling expeditions. Indeed, even in 1993 Fiennes and Stroud needed to be picked up from an ice shelf before reaching its edge, having totally exhausted their energy reserves man-hauling across the Antarctic continent. Thus, even today, while technological advancements have engineered out certain weaknesses of the human condition, others remain as limiting factors that must be stretched to breaking point if explorers on foot are to return home alive from the South Pole.

Acknowledgements
We would like to thank Peter Clarkson, Adrian McCallum, Denis Wilkins, Tom Davies, Ben Edwards and Mark Hines for their comments on drafts of the essay. An especial thank you goes to Heather Lane at the Scott Polar Research Institute for her support during this project.

References
1. Massey, P. (1959). Finger numbness and temperature in Antarctica. J. Appl. Physiol. *14*, 616–620.
2. Zuntz, N. (1906). Höhenklima und Bergwanderungen in ihrer Wirkung auf den Menschen, (Berlin: Bong).
3. Stroud, M. (1998). The nutritional demands of very prolonged exercise in man. Proc. Nutr. Soc. *57*, 55–61.
4. Westerterp, K.R., Saris, W., van Es, M., and Ten Hoor, F. (1986). Use of the doubly labelled water technique in humans during heavy sustained exercise. J. Appl. Physiol. *61*, 2162–2167.
5. Marshall, E. (1943). Off the beaten track. In The Medical Press and Circular, Volume 8. pp. 359–362.
6. Rogers, A. (1981). The influence of diet in Scott's last expedition. In Starving Sailors. The Influence of Nutrition upon Naval and Maritime History, J. Watt, E. Freeman and W. Bynum, eds. (London: National Maritime Museum), pp. 163–173.
7. Tsintzas, O., Williams, C., Singh, R., Wilson, W., and Burrin, J. (1995). Influence of carbohydrate-electrolyte drinks on marathon running performance. Eur. J. Appl. Physiol. *70*, 154–160.
8. Speth, J., and Spielmann, K. (1983). Energy source, protein metabolism, and hunter-gatherer subsistence strategies. J. Anthropol. Archaeol. *2*, 1–31.
9. McArdle, W., Katch, F., and Katch, V. (2007). Exercise at medium and high altitude. In Exercise Physiology Energy, Nutrition and Human Performance, W. McArdle, F. Katch and V. Katch, eds. (Philadelphia: Lippincott Williams & Wilkins).
10. Grandjean, A., and Grandjean, N. (2007). Dehydration and Cognitive Performance. J.e Am. College Nutrition *26*, 5498–5548.
11. Wright, A. (1900). On the pathology and therapeutics of scurvy. Lancet *156*, 565–567.

[1]Roehampton University, Holybourne Avenue, London SW15 4JD, UK. [2]NIHR Biomedical Research Unit in Nutrition, Southampton University Hospitals Trust, Southampton SO16 6YD, UK.
*E-mail: l.halsey@roehampton.ac.uk

Correspondence

Rocking synchronizes brain waves during a short nap

Laurence Bayer[1*], Irina Constantinescu[1*], Stephen Perrig[2], Julie Vienne[3], Pierre-Paul Vidal[4], Michel Mühlethaler[1*] and Sophie Schwartz[1,5*]

Why do we cradle babies or irresistibly fall asleep in a hammock? Although such simple behaviors are common across cultures and generations, the nature of the link between rocking and sleep is poorly understood [1,2]. Here we aimed to demonstrate that swinging can modulate physiological parameters of human sleep. To this end, we chose to study sleep during an afternoon nap using polysomnography and EEG spectral analyses. We show that lying on a slowly rocking bed (0.25 Hz) facilitates the transition from waking to sleep, and increases the duration of stage N2 sleep. Rocking also induces a sustained boosting of slow oscillations and spindle activity. It is proposed that sensory stimulation associated with a swinging motion exerts a synchronizing action in the brain that reinforces endogenous sleep rhythms. These results thus provide scientific support to the traditional belief that rocking can soothe our sleep.

In the present study, we asked twelve healthy male volunteers (22–38 years old) to nap on a bed that could either remain stationary or rock gently (0.25 Hz; Figure 1A). All participants were good sleepers, non-habitual nappers with no excessive daytime sleepiness and had low anxiety levels. Sleep quality and quantity were assessed by questionnaires and actimetry recordings. The experimental procedure involved taking two 45-minute afternoon naps (2:30 to 3:15 PM): one with the bed stationary, and one with the bed put in motion (condition order randomized). The motion parameters were set to stimulate vestibular and proprioceptive sensory systems, without causing nausea or any entrainment of cardiac rhythm. In both conditions the naps were spent in complete darkness in a controlled room temperature (21 ± 1°C) and the level of auditory stimulation was around 37 dB. During both sessions, polysomnography data were recorded continuously. Sleep stages and sleep spindles were visually identified by two experienced scorers, blind to the experimental conditions. We also performed spectral analysis (FFT routine) using the midline frontal (Fz) and parietal (Pz) derivations. The data from two participants were excluded from the final analyses (see the Supplemental Information).

Over the three consecutive nights preceding each experimental day, all participants had a good quality and quantity (mean ± s.e.m.; 7.32 ± 0.78 h) of sleep as assessed by self-rated sleep questionnaires, with no difference for these measurements between stationary and swinging conditions. Similarly, wrist actimetry recorded during these same nights did not show any difference in sleep efficiency between conditions (mean ± s.e.m.; swinging: 86.63 ± 1.95%; stationary: 86.71 ± 1.23%). For both conditions, participants were more alert (on visual analogue scale) after napping than before ($F(1,9) = 8.4$, $P = 0.018$). Eight participants rated the swinging condition as 'more pleasant' than the stationary condition; for one participant both sessions were equally pleasant and for one participant the stationary condition was more pleasant.

We found that rocking accelerated sleep onset, as evidenced by a shorter duration of stage N1 sleep and a reduction of stage N2 latency, compared to the stationary condition (Supplemental Table S1). Rocking also affected deeper sleep stages by increasing the duration of stage N2 sleep and the mean spindle density per 30-s epoch (Supplemental Table S1, Figure 1B). Spindle density increased significantly from the second half of the nap (Figure 1C) and persisted throughout the entire duration of stage N2 (Supplemental Figure S1A). All these modifications were observed in each and every participant (all $P < 0.009$; Supplemental Table S1). In the only previous study investigating the effect of rocking on sleep, Woodward *et al.* [1] found no consistent modulation for the percentage of stage 1 sleep and an overall reduction of the percentage of stage 2 sleep during the motion condition. In contrast to our present